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A SUMMARY OF WIND TUNNEL RESEARCH ON TILT-ROTORS FROM HOVER TO CRUISE FLIGHT

REVUE DES ÉTUDES EN SOUFFLERIE SUR LES ROTORS BASCULANTS, DU VOL STATIONNAIRE AU VOL DE CROISIÈRE

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et Woodrow L. COOK (NASA Ames Research Center)

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(texte en anglais)

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REVUE DES ÉTUDES EN SOUFFLERIE SUR LES ROTORS BASCULANTS, DU VOL STATIONNAIRE AU VOL DE CROISIÈRE

Dans le cadre d'un accord de coopération NASA/ONERA, un programme de recherches expérimentales a été conduit sur une famille de rotors basculants destinés à des VTOL convertibles à grande vitesse ; les essais ont été effectués dans diverses installations d'essais aux U.S.A. et en France depuis le point fixe jusqu'à un nombre de Mach de 0,7 environ :

- banc point fixe de l'U.S. Air Force à Wright-Field,
- installation d'essais de l'U.S. Army à Ames,
- grande soufflerie 40 × 80 pieds de la NASA à Ames,
- soufflerie sonique de 8 m, S1 de l'O.N.E.R.A. à Modane.

L'objectif principal de cette recherche était d'obtenir des résultats précis sur l'influence du vrillage et de l'élasticité des pales sur les performances d'un rotor basculant dans tout le domaine de vol.

Cinq rotors rigides en duralumin avec diverses lois de vrillage, et un rotor aéroélastique en fibres de verre (diamètre : 4 m) ont été essayés, à l'échelle 1/4 environ d'un convertible typique calculé pour une vitesse de croisière supérieure à 300 nœuds.

Les efforts globaux sur le rotor, les contraintes locales et les déformations de pale ont été comparés avec les prévisions théoriques dans un domaine étendu de nombres de Mach et de Reynolds.

On décrit ici certaines techniques nouvelles d'essais développées à l'occasion de ce programme de coopération et on donne un bref résumé des principaux résultats obtenus dans les deux pays.

A SUMMARY OF WIND-TUNNEL RESEARCH ON TILT-ROTORS FROM HOVER TO CRUISE FLIGHT

by

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SUMMARY

Within the framework of a cooperative agreement between NASA and ONERA, an experimental research program has been conducted on a series of tilt rotors designed for a range of blades twist in the various wind tunnel facilities of the NASA, ONERA and the USAAMRDL. The facilities include the NASA/Ames 40 x 80-foot Wind Tunnel, ONERA/Modane 8 meter sonic wind tunnel and the USAAMRDL/Ames 7- by 10-foot Wind Tunnel as well as the Air Force static test facility at Wright-Patterson.

The main objective of the experimental program was to obtain precise results about the influence of blades twist and aeroelasticity on tilt rotor performance, from hover to high speed cruise Mach number of about 0.7.

Five aluminium "rigid" rotors with various blade twists , and one fiberglass composite "dynamicaly scaled" rotor were tested (scaled 13/55th and 5/55th from a typical 55ft tilt rotor aircraft design) ; global forces on the rotor, local loads and blade torsional deflection measurements were compared with theoretical predictions inside a large Reynolds-Mach envelope. This paper describes some new testing techniques developed for this joint program and gives a brief summary of the main results obtained in the U.S. and French facilities.

NOTATION

C_d	Section drag coefficient
C_l	section lift coefficient
C_T	thrust coefficient, $T_N/\rho n^2 D^4$
C_p	power coefficient, $P/\rho n^3 D^5$
c	blade chord
D	rotor diameter, feet
D_S	spinner drag
FM	figure of merit, $0.798 \frac{C_T^{3/2}}{C_p}$
J	advance ratio, V_o/nD, with $n = \frac{rpm}{60}$
J'	$\frac{V_o \cos\alpha}{nD}$, with α : rotor tilt angle
M	Mach number
P_b	spinner base pressure
P_o	free stream pressure
R	rotor radius
$\bar{R}$	r/R, local blade station radius ratio
R_e	Reynolds number
S_b	spinner base area
T_G	gross thrust
T_N	net thrust, $T_G + D_S$
V_o	free stream velocity
V_t	velocity at blade tip

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t	blade section thickness
α	rotor tilt angle
β	rotor blade pitch angle
$\Delta\beta$	blade twist angle, incremental or total
σ	rotor solidity
ρ	density
η	blade efficiency at forward speed.

INTRODUCTION

The tilt-rotor concept is one of the most promising candidates for future VTOL Aircraft because it provides a good compromise in design requirements for both hover and high speed cruise flight ; but two main problems must be carefully studied :

- compromise of geometry for aerodynamic optimization of hover and cruise efficiencies,
- aeroelastic behaviour of the rotor itself, and elastic coupling between rotors and airframe [Réf. 1]

To answer a part of these problems, the Research Program summarized in this paper was initiated by NASA (AMES Research Center, Advanced Aircraft Programs Office) and US Army Aeronautical Research Laboratory with a contract to the Boeing Company, Vertol Division ; the contract objective was to experimentally verify predicted levels of hovering and cruise performance [2]; this program was conducted as a joint NASA/ONERA effort under an International Cooperative Agreement established in 1968 ; the agreement provided for the use of French and U.S. facilities and for an exchange of the resulting data.

The need for a compromise in the design requirements between hover and cruise flight of a tilt-rotor Aircraft is illustrated in figure 1 :

in hover flight (H), the requirement for efficient performance are high thrust coefficient, high rotational speed (RPM) and small values of blade twist, whereas the requirements for efficient cruise performance (C) are low thrust coefficients, relatively lower RPM, and larger values of blade twist. Typical rotor radial variations of loads and local Mach number for hover (H) and cruise (C) are also given in figure 1, which illustrates the great difference in local lift coefficient and local Mach number for the two conditions of flight.

DESCRIPTION OF TILT ROTORS

The 4 meter (13 foot) diameter rotor models are scaled from a 55-foot diameter design by Boeing-Vertol (low disc loading Tilt Rotor Aircraft, see figure 1).

The 4 m diameter was chosen in order to permit extensive tests in various facilities, including the 40 x 80 ft Ames Tunnel, the AFAPL-USAF test stand, and the ONERA - S_1 Modane sonic 8-meter diameter tunnel. Figures 2 and 3 give the general characteristics of the rotors.

The rotors have a 6-percent thickness at the rotor tip, varying to 10-percent at about 30-percent of the rotor radius. Inboard of 30-percent, due to structual requirements of the smaller 4 m rotor, it was necessary to increase the thickness rapidly to a value of 33-percent thickness at 15-percent radius. This increase in thickness had a negative effect on high speed cruise performance ; however, survey rakes measurements were included in the tests to determine the performance loss due to the increased thickness which resulted in a 2 to 3-percent reduction in efficiency at the Mach number range from 0.5 to 0.68. Five semi-rigid rotor designs, each having a different total value of blade twist: 26.6°, 29°, 36°, 40.9° and 44° were tested. The detailed variation of thickness at several radial stations for the rotors and the variation of blade twist for blades D, E and F (44, 36 and 26,6 degrees of twist respectively) are shown in figure 3.

HOVER PERFORMANCE

The calculated variation of local lift coefficient along the blade radius (figure 4a) shows that, with the 44° twisted blades, a large inner part of the rotor penetrates the predicted stall boundaries, whereas the lowest 26.6° twisted blades is far from the separation regime ; this explains the large computed difference in hover efficiency (figure of merit) at the design conditions (V_{tip} = 230 m/sec, 6000 ft altitude) shown on figure 4b ; experimental results obtained on these two 13 ft rotors are in good agreement with the predicted (F.M., C_T) trend : the loss in rotor hover performance is about 7-percent at 44° twist compared to 26.6° twist.

The variation of the hover figure of merit measured for the five rotors as a function of their twist from the two test facilities (Ames 40 x 80 ft wind tunnel and U.S. Air Force static test rig) is given on figure 5a for the optimum thrust coefficient C_T = 0.075 : experimental values are in close agreement with the predicted F.M, and decrease when the blade twist increases.

The variation of figure of merit with rotor blade tip Mach number (figure 5b) and thrust coefficient (figure 5c) indicate a rapid reduction in figure of merit at tip Mach above about 0.8, and a severe reduction in figure of merit occurs at thrust coefficients above about .09. for a given tip Mach number. The data and calculated values indicated that, at design conditions (tip Mach number of 0.67 and thrust coefficient of 0.075) the figure of merit values range from a maximum of about 0.79 for the lower values of twist below 30° to less than 0.72 for values of blade twist greater than 44 degrees.

To illustrate the scale effect, figure 6 presents the variation of figure of merit as a function of thrust coefficient for the 13-foot rotor and for the 5-foot rotor tested by the U.S. Army (AARL Static rig), with the same 36° twist law.

A 5-percent loss in figure of merit with the smaller scale 5-foot diameter rotor at the design C_T can be explained by a Reynolds number effect already evidenced on higher disc loading propellers (see figure 6, profile drag versus Re, and Ref. 1).

The 13-foot rotor falls on the flat part of the curve (F.M., Re) above critical Reynolds number, whereas the 5-diameter rotor (mean Reynolds number of 0.7 million) is on the steep part of the curve. From these curves it would be expected that a 55-diameter rotor would have about 2 percent higher figure of merit than the 13-foot diameter rotor and also that the low disc loading proprotor having about 10 to 12 pounds per square foot disc loading would have from 1.5 to 2-percent lower figure of merit than the maximum performance envelope values for higher disc loading propellers.

About hover performance measurements on scaled rotor models, a new method has been recently developed in the ONERA S_1 Modane wind-tunnel, based on an extrapolation to zero speed of the results obtained at very low speed inside the closed test section (figure 7).

For the first time, it was possible to check the validity of this method by comparison with "true" static tests obtained with the same 13 ft rotor on the U.S.A.F./Wright-Field rig : it can be seen in figure 7 that the extrapolated results on power and thrust coefficients obtained at very low values of the advance ratio J in S_1 Modane are in close agreement with those measured on the special AF/APL static facility ; also shown, on the (C_T, J) graph, is the theoretical trend, assuming that C_P and F.M. at low J values are the same as those obtained on a static rig at J = 0 (from the relationship :

$$F.M. = \frac{CT}{CP}\left(\frac{J}{2}+\sqrt{\left(\frac{J}{2}\right)^2+\frac{2}{\pi}C_T}\right).$$

To use such low test speed it is necessary :

- to stop the wind-tunnel fans,
- to fit a low permeability screen to the rear of the first diffusor (to reduce the mass flow induced by the rotor inside the return circuit),
- to measure this very low speed with special instrumentation (double-venturi tube).

Finally, the speed was reduced to 2-4 m/sec with the lowest screen porosity, but attained 10-15 m/sec without any screen at the first diffusor exit.

FORWARD SPEED TESTS, RIGID BLADES

Shown in figure 8 is a shematic of the ONERA/Modane 8-meter test facility and the two test rigs used for these investigations wherein one rig is utilized for low speed tests for a large range of tilt angles, 0 to 10-degrees, with a minimum sized after body (this later rig was also used for the previous "quasi-static" tests).

This large tunnel [Réf. 3] has a continuous operating mode with three interchangeable test sections, one of them being mainly used for rotor and propeller, driven by a group of gas turbines (1000 HP); the tunnel is powered by two counter-rotating fans driven by hydraulic turbines (2 x 55000 HP) ; the stagnation pressure is atmospheric p_{st} = 0,9 bar, at the local 3300 ft altitude) ; the circuit cooling is obtained by air exchange ; the test speed can reach Mach 1, but for the purpose of these rotor tests the Mach number was limited to about 0.7.

TILT ROTOR TRANSITION REGIME

One of the goals of the cooperative NASA/ONERA program was to compare the results obtained on the same rotor (S_R = 12, 5 m²) inside two very different test section sizes, at Ames (S_T = 265 m²) and at Modane (S_T = 50 m²), during the transition regime of flight. The effect of tunnel wall on tilt rotor test data, particularly at low speed and high tilt angles, has been the subject of considerable controversy and discussion. The 13-foot diameter rotor was tested in the Ames 40- by 80-foot wind tunnel through a range of tilt angles from 0 to 78° and a range of speeds. The tunnel wall effects of the 13-rotor in the 40- by 80 foot wind tunnel are presumably very small at disc loading of 10 pounds per square foot and at this very low area ratio $S_R/S_T \cong 5\%$. The same rotor 13-foot diameter was tested under the same tilt angle and velocity conditions in the 26-foot or 8-meter wind tunnel wherein the area ratio S_R/S_T is very large : 25% ; some investigators have claimed that this ratio would be too great to even consider testing. Nevertheless, the results of these tests in the two wind-tunnels are shown in figure 9: The thrust coefficient as function of the effective advance ratio J' which is J cos α (α, angle of tilt) indicates that there is good correlation between the results of the tests in the two wind-tunnels and thus the tunnel wall effects of the 13-foot rotor tested in the ONERA 8-meter wind tunnel are of little significance for research studies of this type of VSTOL propulsion system, at low disc loading. Figure 9 shows that the previous hover tests in the 40' x 80' Ames tunnel (made with open overhead wind-tunnel doors to minimize from recirculation) give a good extrapolation at J' = 0.

CRUISE TESTS

The cruise mode (axial flow) investigation was conducted at the S_1 Modane tunnel on a special axial support system (D_b = 0,6 m) equiped with an internal 6 component balance ; because the axial forces measured on the dynamometer included the drag of the spinner, it was necessary to tare this drag to obtained the "net" thrust in view of comparisons with rotor performance predictions ; Figure 10 explains the two successives methods used for measuring the spinner tare drag :

The first one is based on a spinner base pressure technique : the spinner form drag coefficient was determined from "blades-off" total balance force and base pressure measurements ; during the rotor tests themselves, the total spinner drag D_S was obtained by adding this form drag to the base pressure drag (measured under rotor operating conditions),and then the net thrust was given by $T_N = T_G + D_S$, T_G being the measured gross thrust.

A more satisfactory method was later used where a special balance inside the spinner gives directly its drag with the blades-on and rotating ; a comparison between these two methods seems to indicate that this later method, taking account of the presence of the blades inflow, gives a little larger spinner drag, i.e. a higher cruise efficiency (between 1% and 2%).

This spinner tare drag was found to be a very significant part of the thrust measurements as shown in figure 11 : the gross thrust T_G measured had negative values at Mach numbers above 0.6, where the spinner drag D_S became greater than the blade thrust T_N. All the thrust data shown here have the total spinner drag removed and hence the performance characteristics are for the blades alone and do not include the spinner skin friction or profile drag which would exist on the rotor in flight, whereas the base drag would be part of the total aircraft drag. Also shown in figure 11 are typical advance ratio, J, and thrust coefficient values for a tilt rotor aircraft for a range of Mach numbers from 0.3 to about 0.67 which are used in the following analysis (V_{tip} = 180 m/sec, Z = 10.000 ft). For all these results from S_1 Modane tunnel, the conventional Glauert wall corrections have been applied (ratio S_R/S_T = 0,25), but low levels of thrust loading result in small magnitude of these corrections

At a cruise Mach number of 0.455, about 290 knots, the radial section lift coefficients and cruise efficiency for blades D and F, 44.0 and 26.6° of twist are shown in figure 12 : although blade F at 26.6° is the best at hover, its section loading is poor and shows approximately one half of the blade (inboard of about 55-percent radial station) with a negative lift which results in a 15-percent lower value of cruise efficiency than for blade D at 44° where positive section lift coefficients exist except over the outboard 10-percent of the radius.

The data in figure 13 are the thrust coefficient and efficiency (*) for a range of advance ratios at two blade angles at each of three Mach number, M = 0.455, 0.54 and 0.68. The design thrust coefficient variation with J and the resulting efficiency at each Mach number is also indicated. Because of the low disc loading of the rotor the thrust at maximum efficiency of the rotor is not useable and of no value for the normal cruise operation of tilt rotor aircraft having reasonable levels of drag. As shown in the figure the maximum values of efficiency occur at thrust coefficients and hence power coefficients that are 2 to 4 times higher than required for the aircraft with the higher values occurring at the lower Mach number of 0.455. Utilisation of the maximum values of efficiency can only be obtained economically by utilizing rotors or propellers having significantly higher values of disc loading of the order of 250 to 350 daN/m^2 (50 to 70 pounds per square foot) instead of about 50 daN/m^2 (10 lb/sq.ft) chosen here.

The data shown in figure 14 summarize the measured cruise efficiency for blades D, E, and F over the Mach number range tested 0.3 to 0.72 and the variation of cruise efficiency with the five differently twisted blades for 0.455 and 0.606 Mach number :

- High Mach number tests ($0.5 < M < 0.72$), i.e. above the rotor design calculation (M = 0.455, see Ref. 2), were run to investigate compressibility effects on cruise mode tilt-rotor performance ; figure 14a shows a large decrease of the cruise efficiency above $M \simeq 0.6$ due partly to the large profile thickness (33%) at the blade root (required for structural conditions on these scaled models).

- The blade twist effect (figure 14b) is very important, the best efficiency being obtained with the largest blade twist tested (i.e. an opposite trend than shown in hover) ; the calculated values given here for M = 0.455 [Ref. 2] takes into account the measured velocity profile at the disc plane (a small flow acceleration was detected around the "minimum body" in S_1 Modane tunnel) ; the predicted values are higher than those measured, mainly at the lowest blade twist ; for the "E" blade (36° Twist) the experimental cruise efficiency is 0.71 against 0.745 predicted.

To conclude about the need for a compromise between the performances obtained in hover and in cruise modes, figure 15 gives the measured and predicted values of hover figure of merit as a function of the design cruise efficiency at M = 0.455 : it appears that a blade twist of about 36° ("E" rotor) seems the best compromise for this typical project (F.M. = 0.775, η_{cr} = 0.71).

(*) The symbols on these graphs are directly reproduced from the automatic plotting of a computer program, which takes account of all the corrections and tares.

FORWARD SPEED TESTS OF AEROELASTICALY SCALED ROTOR

To study the effect of aeroelasticity on rotor performance, a special 13 foot diameter fiberglass model had been designed and built [Ref. 2] with the optimum twist shown previously (type "E'", 36° twist) ; the main purpose of the tests in the cruise mode was to study the effect of Mach number and loading on "live" twist deformation, and the effect of aeroelasticity on rotor/blade stability. Shown in figure 16 is a sketch of the aeroelastics blades and the photographic torsional blade deformation technique utilized to measure the variation of "live twist" during tests of the rotor. In this method, an ultra high speed photographic flash unit was used to obtain stop action photographs of the back face of one of the rotating blades which was painted with triangular targets at regular spanwise intervals. The angular difference between a pair targets and the blade root reference targets is related to the blade radial twist distribution. A comparison of this measured distribution under forward speed conditions is made with that of the static twist distribution with the blades nonrotating which gives the instantaneous aeroelastic torsional deflection for various radial stations. A comparison for a typical test point is also shown in figure 16 which indicates about a 2 degree torsional deflection near the rotor tip. An interesting aspect of the measurements was that the so called "rigid blades" (built of aluminium)had noticable blade deformation as shown in figure 17 and that there was a consistant one degree greater twist deformation with the aeroelastic blades than with the "rigid blades" over the entire Mach number and advance ratio, J, range tested as shown in the figure.

The variation of thrust coefficient and efficiency for Mach numbers of 0.455, 0.54 and 0.606 for a range of advance ratios for the aeroelastic blades is compared in figure 18 to the rigid blade data shown previously. Although there is a significant increase in the sharpness of the slope of thrust coefficient variation with advance ratio, the actual cruise efficiency for the cruise Mach numbers is nearly equal to the cruise efficiency with the rigid blades, again indicating a very small twist deformation equivalent to the 1 degree measure. The steepness of the thrust coefficient curve with velocity for the aeroelastic rotor relative to the rigid rotor may be of great concern at the higher Mach numbers due to the potential high sensitivity of thrust to speed and blade angle. This sensitivity made it difficult to control thrust during the wind tunnel tests particularly near values of low or negative thrust where instabilities did occur with the aeroelastic rotor, and prevented testing above a Mach number of 0.606 (the "rigid" rotor was tested to a Mach number of 0.72 with no indication of instability).

A summary curve is shown in figure 19 which compares the measured cruise efficiency for the 36 degree twisted blade rotor for the various rigid and aeroelastic blade rotors tested since 1968 with the calculated cruise efficiency for the same rotor. As can be seen above a Mach number of about 0.45 the test data shows a significant lower cruise efficiency than calculated. At 0.72 Mach number the measured values are of the order of 0.45 whereas calculated is near 0.65. The correlation of the various test data is good in as much as the accuracy of the test data is ± 0.01 in efficiency.

In figure 22 is shown a trace of a specific divergence of rotor loads at a Mach number of 0.63 with the aeroelastic blades that prevented any further tests above a Mach number of 0.606. As can be seen, a rapid and divergent increase in thrust (on the main balance) and in local blade-element torsion and chordwise stress (measured at 23% and 25% R, see figure 21) were measured ; a blade flutter occurred prior to the quick stop initiated as these measurements were being monitored. Further analyses on stress data measured on this elastic rotor, taken at 10 degree angle of attack at low Mach number (figure 21), in an effort to better understand the stability problem that was encountered during the tests. But it must be remembered that the Mach number of 0.63 where the instability or flutter occurred is significantly above the anticipated design cruise Mach number of about 0.46 for potential tilt rotor type aircraft being considered.

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[2] BOEING-VERTOL Cy- Investigation of the performance of low disc-loading tilt rotors in hovering and cruise flights (NASA contract NAS2-5025) - BOEING/Vertol Division report D160 - 10013 - 1 and 2, March 1971.

[3] PIERRE M. - Caractéristiques et possibilités de la grande soufflerie sonique de Modane-Avrieux.
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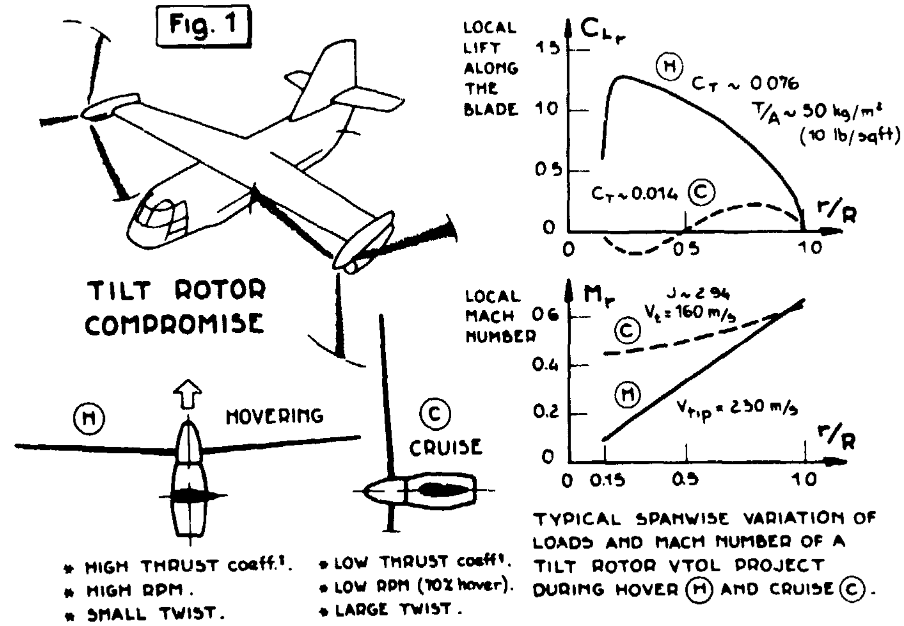


Fig. 1
TILT ROTOR COMPROMISE
(H) HOVERING
(C) CRUISE
* HIGH THRUST coeff.t.
* HIGH RPM.
* SMALL TWIST.
• LOW THRUST coeff.t.
• LOW RPM (70% hover).
• LARGE TWIST.
LOCAL LIFT ALONG THE BLADE
C_{L_r}
(H) $C_T \sim 0.076$
$T/A \sim 50$ kg/m² (10 lb/sqft)
$C_T \sim 0.014$ (C)
r/R
LOCAL MACH NUMBER
M_r
J ~ 2.94
$V_t = 160$ m/s
$V_{tip} = 230$ m/s
TYPICAL SPANWISE VARIATION OF LOADS AND MACH NUMBER OF A TILT ROTOR VTOL PROJECT DURING HOVER (H) AND CRUISE (C).

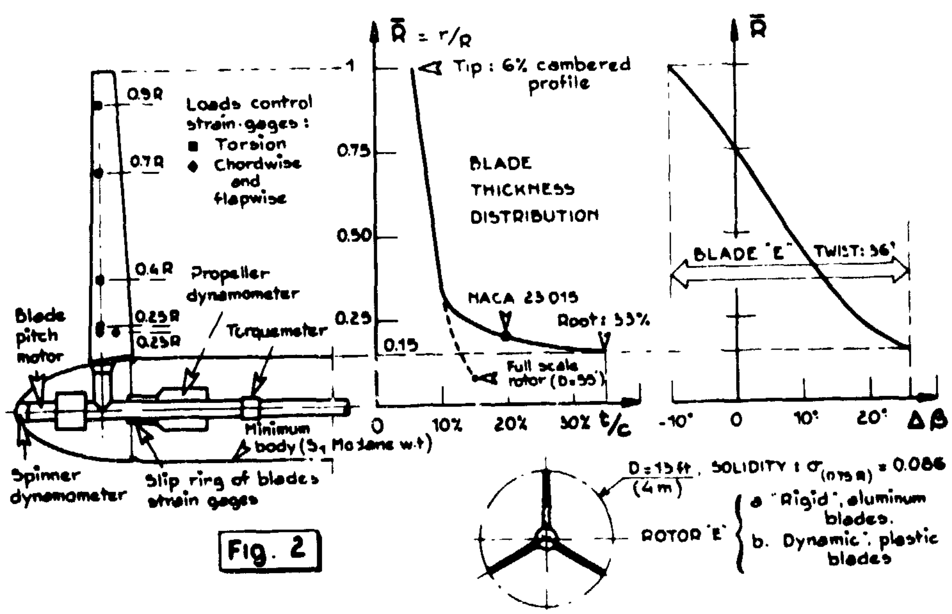
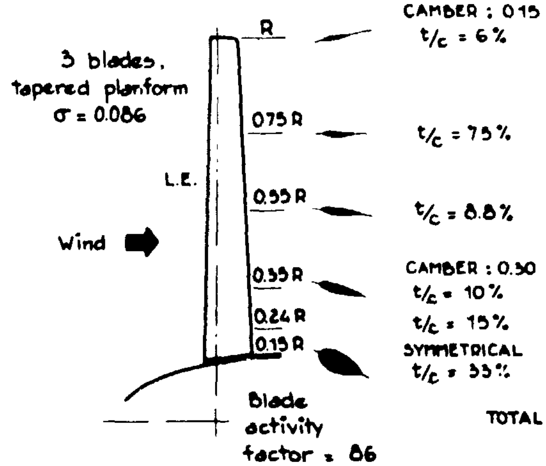

0.9R
0.7R
0.4R
0.25R
0.25R
Loads control strain-gages:
■ Torsion
◆ Chordwise and flapwise
Propeller dynamometer
Torquemeter
Blade pitch motor
Spinner dynamometer
Slip ring of blades strain gages
Minimum body (S1 Modane w.t)
$\bar{R} = r/R$
Tip: 6% cambered profile
BLADE THICKNESS DISTRIBUTION
NACA 23015
Root: 33%
Full scale rotor (D=55')
t/c
BLADE "E" TWIST: 36°
$\Delta\beta$
D = 13 ft (4 m), SOLIDITY : $\sigma_{(0.75R)} = 0.086$
ROTOR "E"
a. "Rigid", aluminum blades.
b. "Dynamic", plastic blades
Fig. 2

Fig. 3

TILT ROTOR
DIMENSIONAL CHARACTERISTICS



TWIST DISTRIBUTION

	BLADE "D"	BLADE "E"	BLADE "F"
R	-12.6°	-10.2°	-6°
0.75 R	0	0	0
0.55 R	8.7°	6.5°	5.3°
0.35 R	15.0°	13.7°	11.0°
0.24 R	23.1°	18.6°	14.9°
0.15 R	31.4°	25.8°	20.6°
TOTAL	44.0°	36.0°	26.6°

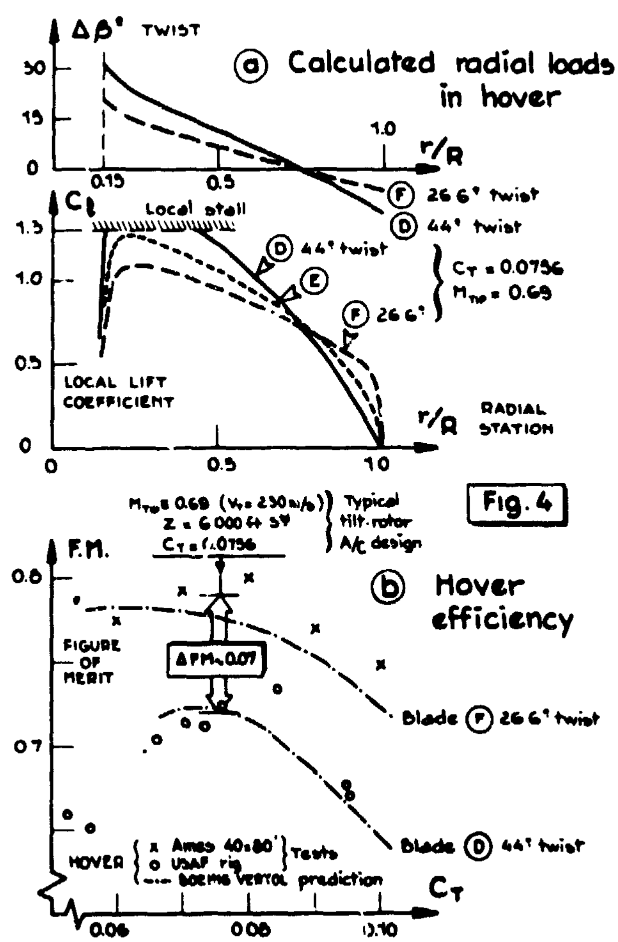


Fig. 4

Fig 5

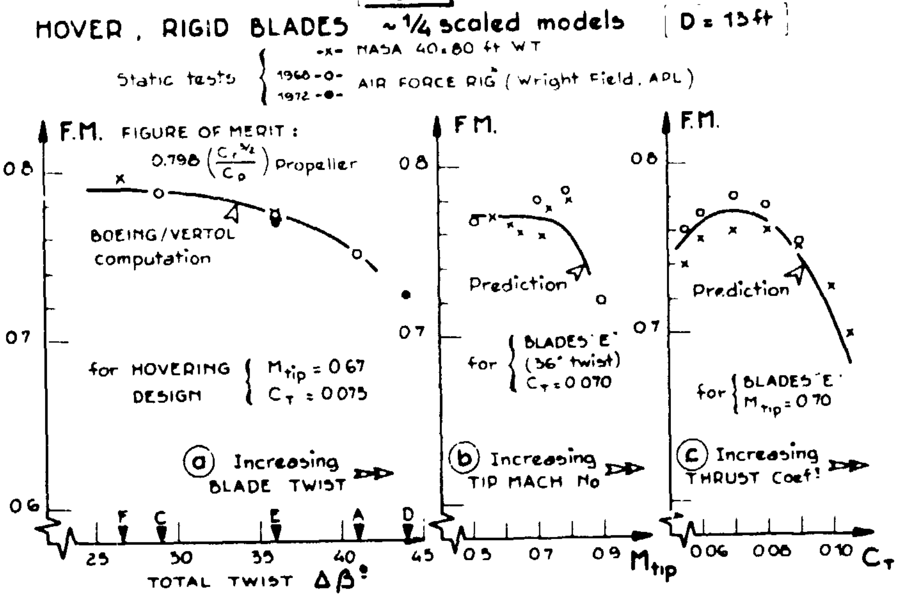
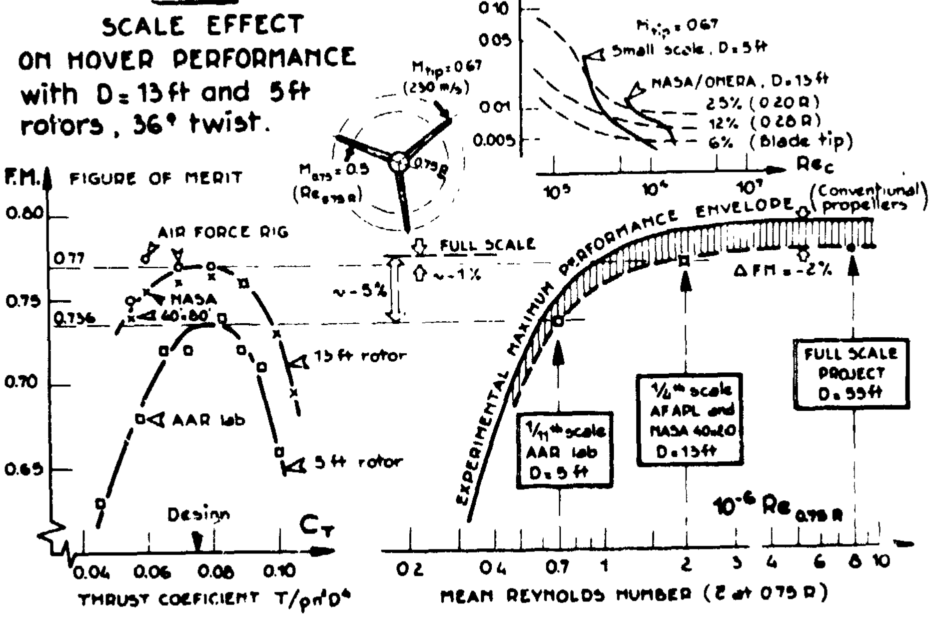

HOVER, RIGID BLADES ~1/4 scaled models
D = 13 ft
Static tests
NASA 40x80 ft WT
1966
1972
AIR FORCE RIG (Wright Field, APL)
F.M. FIGURE OF MERIT :
0.798 (C_T^3/2 / C_P) Propeller
BOEING/VERTOL computation
for HOVERING DESIGN
M_tip = 0.67
C_T = 0.075
(a) Increasing BLADE TWIST
TOTAL TWIST Δβ°
Prediction
for BLADES 'E' (36° twist) C_T = 0.070
(b) Increasing TIP MACH No
M_tip
for BLADES 'E' M_tip = 0.70
(c) Increasing THRUST Coef^t
C_T

Fig. 6


SCALE EFFECT
ON HOVER PERFORMANCE
with D = 13 ft and 5 ft
rotors, 36° twist.
F.M. FIGURE OF MERIT
AIR FORCE RIG
NASA 40x80
AAR lab
13 ft rotor
5 ft rotor
Design
THRUST COEFFICIENT T/ρn²D⁴
M_tip = 0.67 (230 m/s)
M_0.75 = 0.5 (Re_0.75R)
FULL SCALE
~5%
~-1%
C_D min PROFILE DRAG
M_tip = 0.67
Small scale, D = 5 ft
NASA/ONERA, D = 13 ft
25% (0.20 R)
12% (0.28 R)
6% (blade tip)
Re_c
EXPERIMENTAL MAXIMUM PERFORMANCE ENVELOPE
(Conventional propellers)
ΔFM = -2%
1/11th scale AAR lab D = 5 ft
1/4th scale AFAPL and NASA 40x80 D = 13 ft
FULL SCALE PROJECT D = 55 ft
10⁻⁶ Re_0.75R
MEAN REYNOLDS NUMBER (c at 0.75 R)

HOVER PERFORMANCE ON A ROTOR
by extrapolation to J=0 from wind-tunnel tests at very low speed.

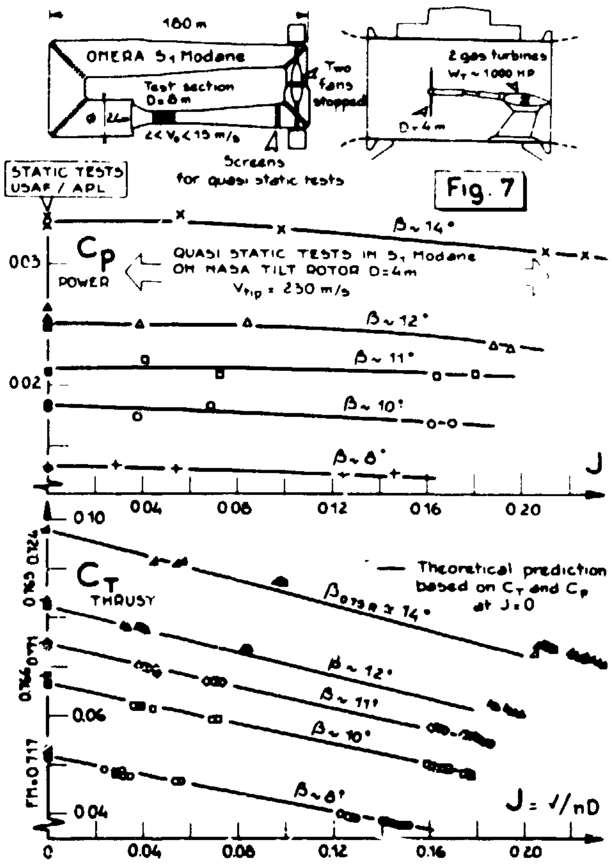
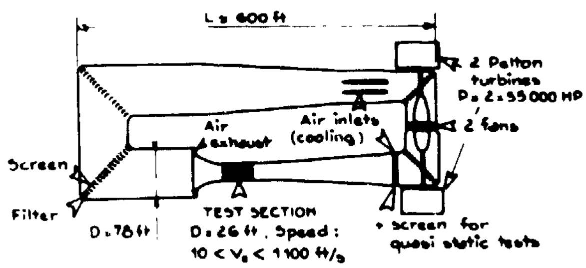


Fig. 7



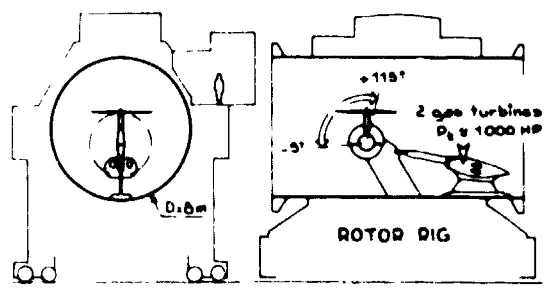
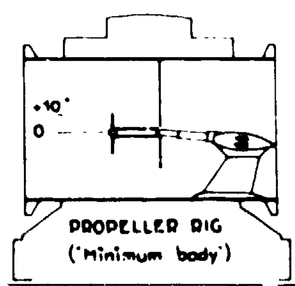


Fig. 8



ONERA TESTS
IN THE SONIC
S1 WIND-TUNNEL

- Helicopter rotors.
- Tilt rotors.
- V/STOL airframe + propellers.

Fig. 9 TILT ROTOR TRANSITION REGIME with "F" 13 ft rotor (26.6° twist). N = 800 rpm.

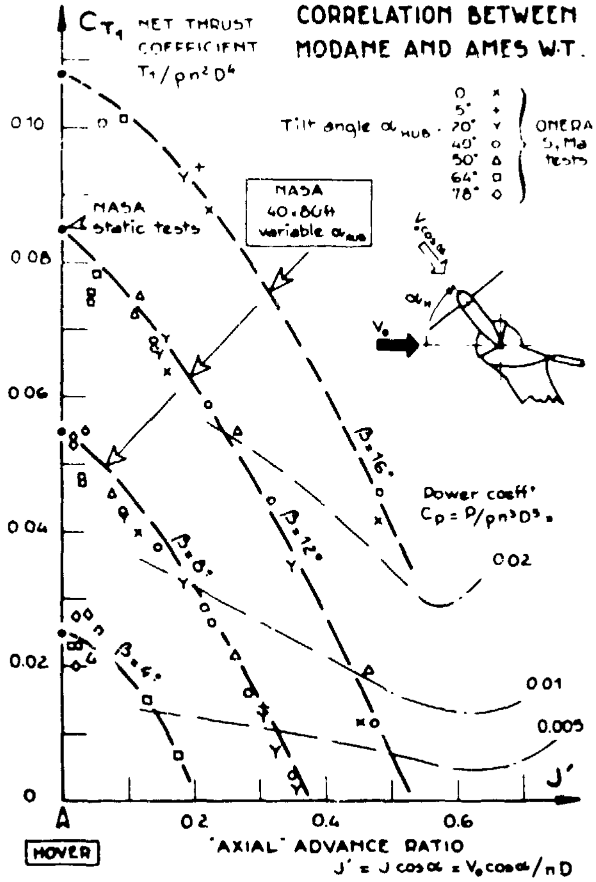
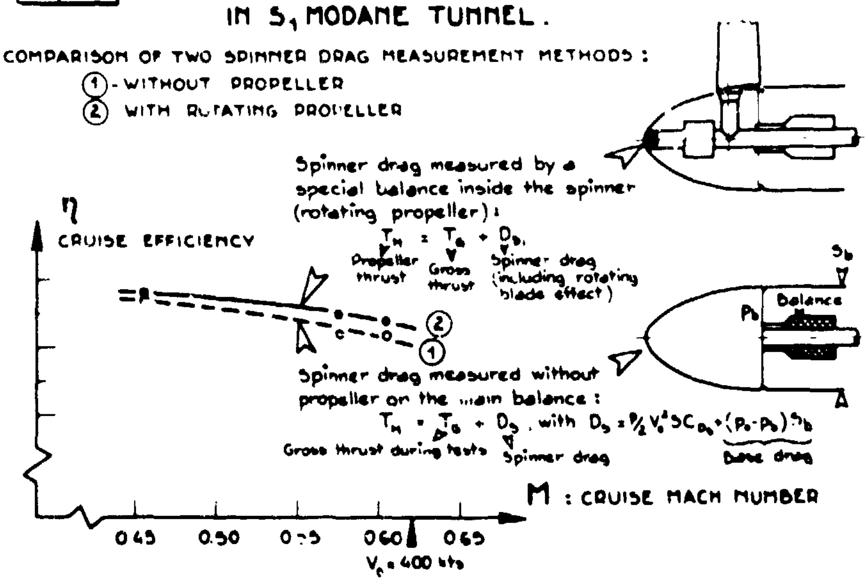
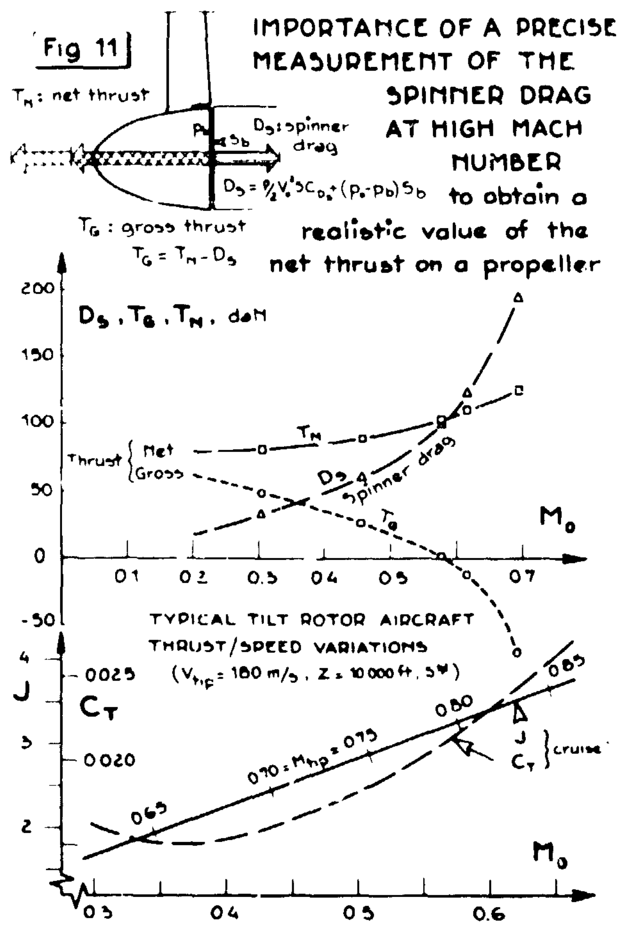
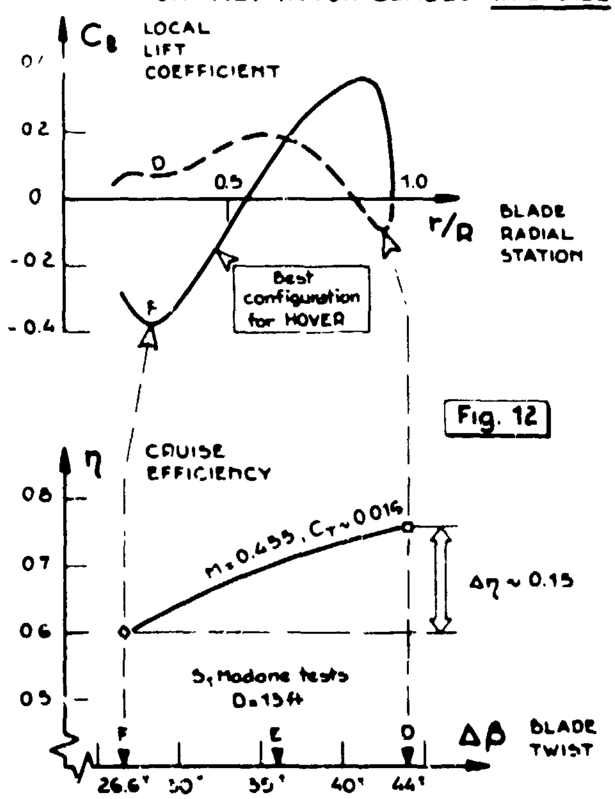


Fig 10 SPINNER TARE DRAG IN S_1 MODANE TUNNEL.





SPANWISE LOAD DISTRIBUTION ON TILT ROTOR BLADES IN CRUISE.



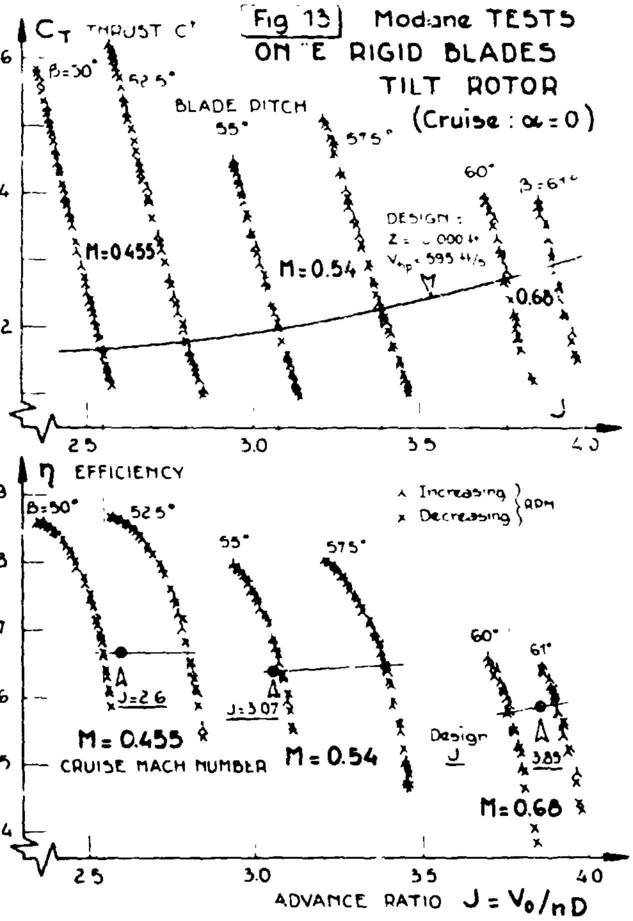


Fig 13 Modane TESTS ON E RIGID BLADES TILT ROTOR (Cruise : α = 0)

Fig. 14

HIGH SPEED PERFORMANCE OF VARIOUS "RIGID" ROTORS IN S1 MODANE

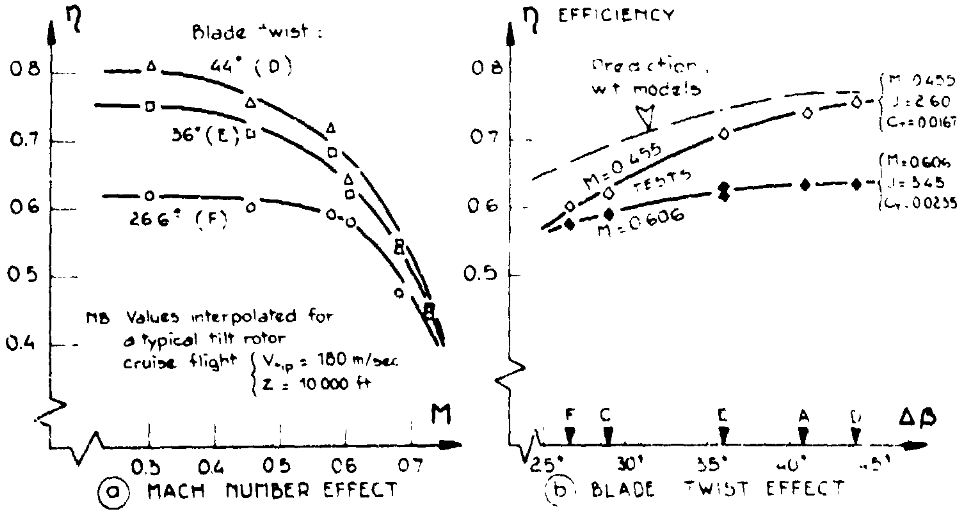
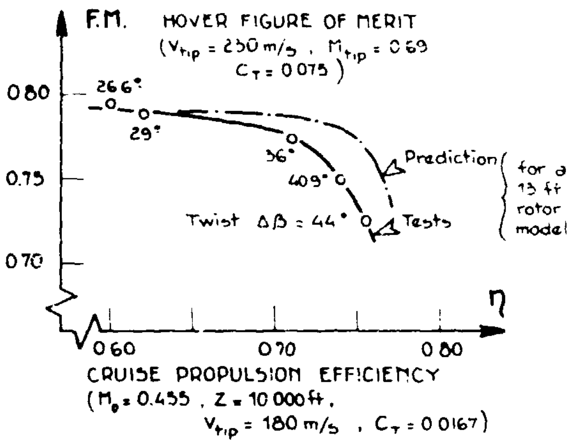


Fig. 15

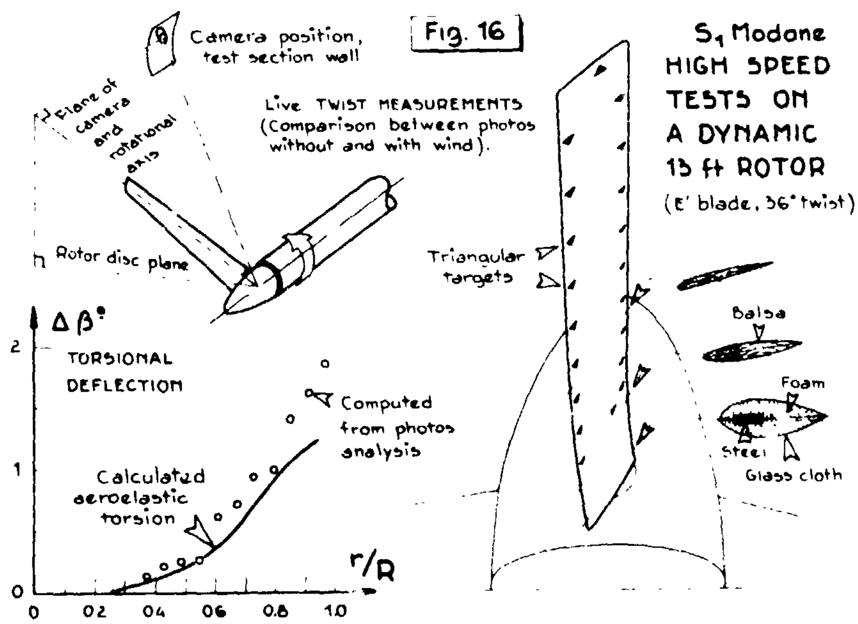


SUMMARY OF TYPICAL TILT ROTOR PERFORMANCES obtained from 13 ft "rigid" models tested by NASA/USAF (HOVER) and ONERA (CRUISE).

Fig. 16

S_1 Modane HIGH SPEED TESTS ON A DYNAMIC 13 ft ROTOR

(E' blade, 36° twist)



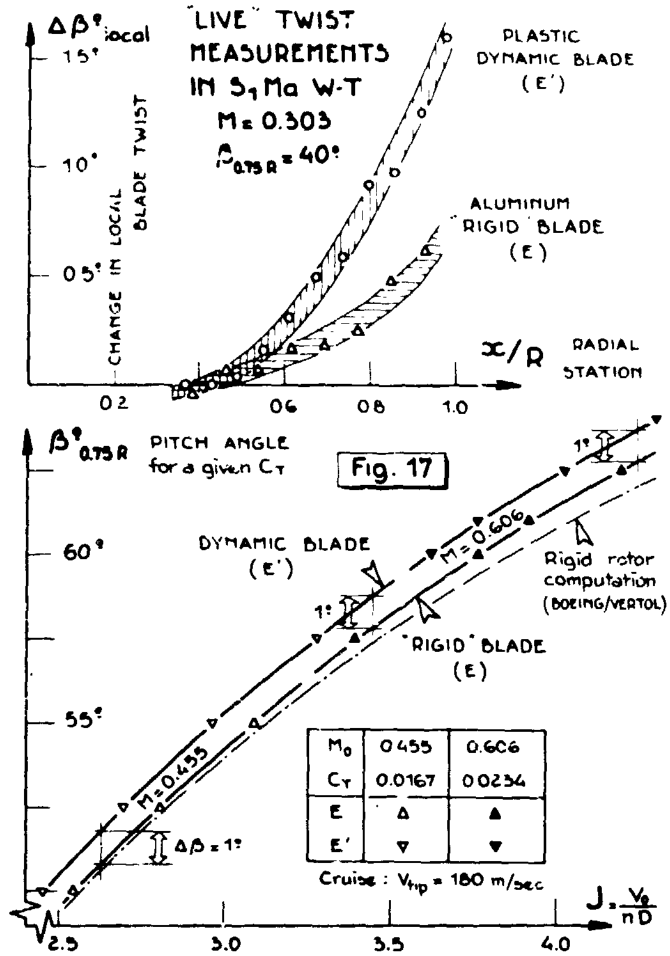


Fig. 18 TESTS ON TWO "36° TWIST" TILT ROTORS (Cruise : α = 0)
Influence of blade elasticity

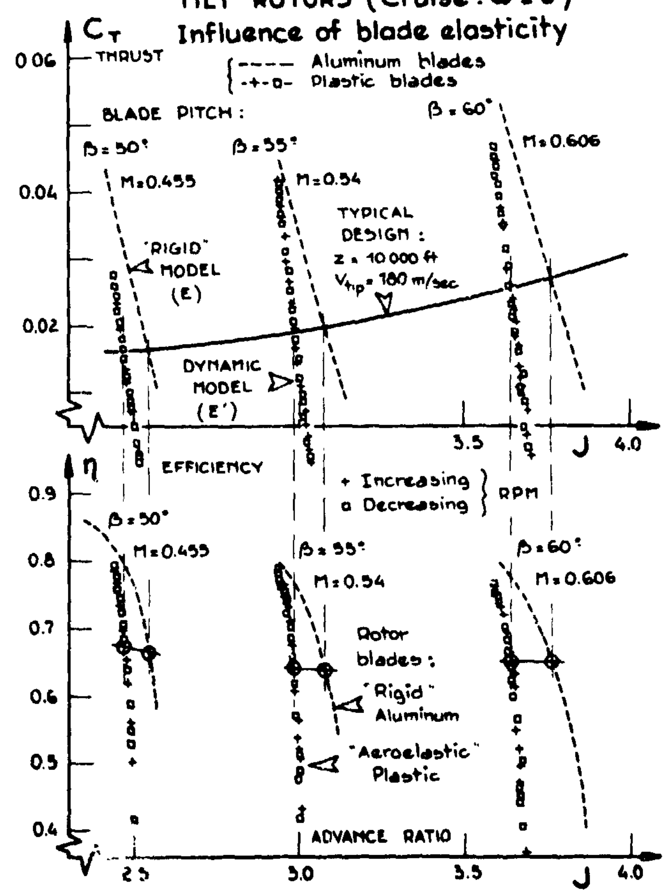


Fig. 19

COMPARISON OF THE MACH NUMBER EFFECT ON CRUISE EFFICIENCY obtained on the "36° twist" rotors in S_1 Modane wind-tunnel.

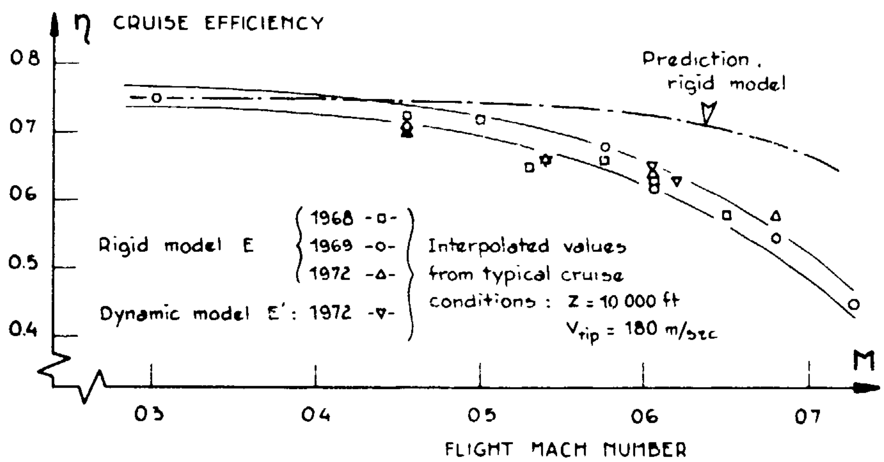
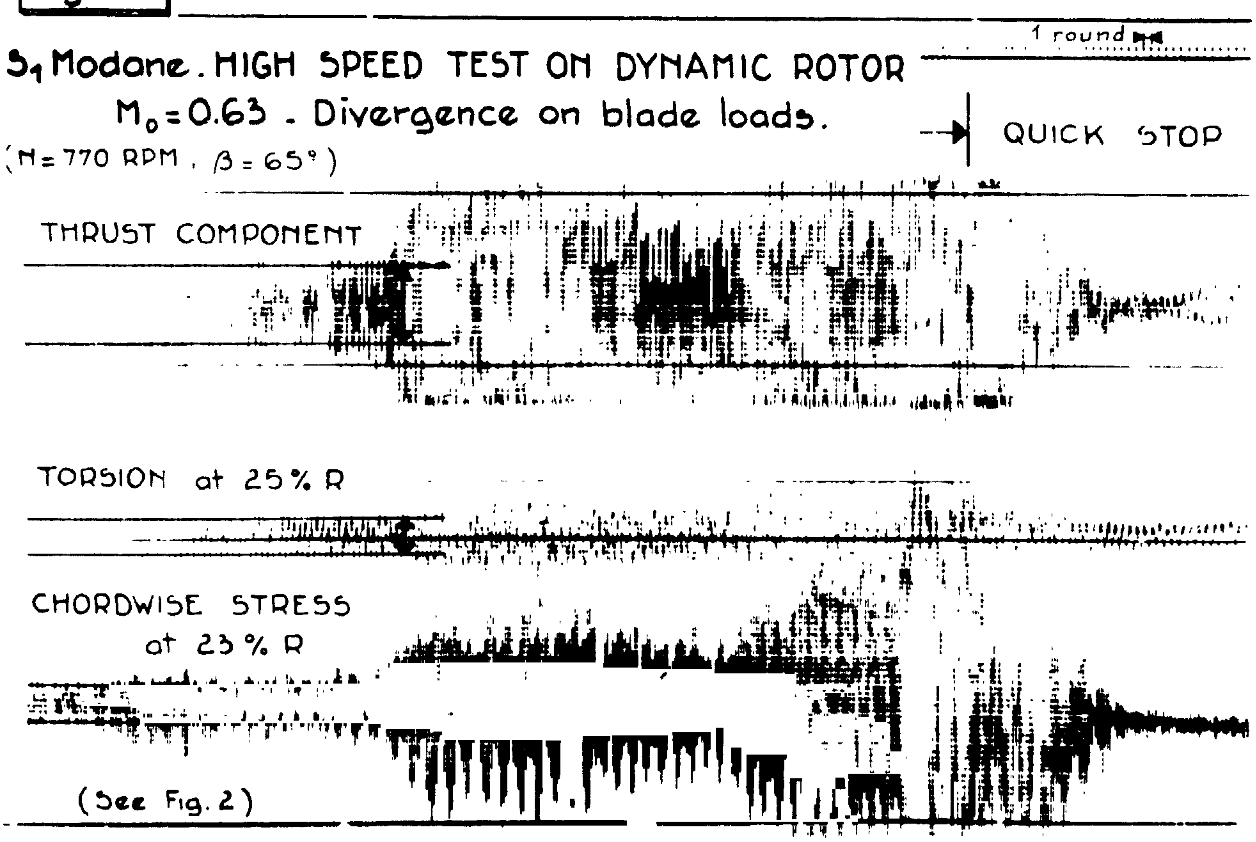


Fig. 20

S_1 Modane. HIGH SPEED TEST ON DYNAMIC ROTOR

$M_0 = 0.63$. Divergence on blade loads.

($N = 770$ RPM, $\beta = 65°$)



(See Fig. 2)

STRESS ANALYSIS ON THE BLADES OF THE "AEROELASTIC" ROTOR (E') with $\alpha = 10°$ in S_1 Modane w.t

Fig. 21